The Influence of a Static Magnetic Field on the Behavior of a Quantum Mechanical Model of Matter

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Abstract—*The paper presents an experimental measurement of a material inserted in various types of magnetic field. The related model accepts the time component of an electromagnetic field from the perspective of the properties of matter. Relatively moving systems were derived and tested [1], and the influence of the motion on a superposed electromagnetic field was proved to exist already at relative motion speeds. In micro- and nanoscopic objects, such as the basic elements of matter, the effect of an external magnetic field on the growth and behavior of the matter system needs to be evaluated. We tested the model based on electromagnetic field description via Maxwell's equations, and we also extended the monitored quantities to include various flux densities. Experiments were conducted with growth properties of simple biological samples in pre-set external magnetic fields.*

Keywords—external magnetic field, numerical model, magnetic flux density, homogenous magnetic field.

I. INTRODUCTION

The authors describe and verify the growth characteristics of simple tissue structures in relation to a present external magnetic field; the results of the research are to clarify the effects of magnetic (geomagnetic) field changes on such cultures. Although the first biological experiments showed that, in the given sense, magnetic fields do exhibit certain statistically significant influence, the question remained of what tools and model parameters are applicable for the description of a complex system embodied in, for example, even a very simple tissue structure. The referenced papers present various approaches to and aims of the investigation of an external magnetic field on the surrounding environment. Roda [2] described the very specific influence of a stationary magnetic (50 µT) and an electromagnetic (6 µT, 50 Hz) field on animal tissues as regards their ability to stimulate or restrain antioxidative enzymes. The effects of stationary gradient magnetic fields (4,3 T/m) on the growth of eukaryotic organisms are discussed in article [3]; the related experiments showed that although the speed and growth phase of the exposed population of Paramecium caudatum do not differ significantly from those observed in check populations, a major negative decrease (by 10.5% to 12.2%) occurs in both the time necessary for the maximum growth of the organism and the number of individuals in a colony (10.2% - 15.1%). Paper [2] presents the conclusions obtained from experiments targeting the influence of a pulse magnetic field (10µT and 100 Hz, with the duty cycle of 2:1 and period of 1s) on fertilized eggs of domestic fowl (Gallus domesticus). After 15 days of the experimental cycle, the exposed embryos exhibited a higher somatic weight and a more advanced stage of development than their control counterparts; at 21 days into the experiment, the somatic weight and stage of development were lower in the exposed embryos than in the control ones. The difference is not discernible in embryos that have been exposed to a magnetic field with harmonic waveform of the frequency of 50 Hz. The experiment [4] proposes that the action of a magnetic field (480 mT) on samples of maize (Zea mays L.) sown in a substrate increases the growability, growth in percent, and weight of the dry sample; however, under action of the magnetic field, the growth of the given type of seed differs depending on its genetic variability. According to an earlier study [5], a strong external magnetic field introduces a basic anisotropy into incompressible magnetohydrodynamic turbulence. The conclusion is reached that the turbulent spectrum splits into two parts: an essentially twodimensional spectrum with both the velocity field and magnetic fluctuations perpendicular to the magnetic field, and a generally weaker and more nearly isotropic spectrum of Alfven waves. The discussed paper [5] comprises an elementary evaluation of the properties of a dynamic environment; the influence of an external magnetic field on a biological system including nanoparticles is then analyzed, together with the activation of such a system, in article [6]. In this context, let us note that activated platelets play a pivotal role in cardiovascular diseases such as atherothrombosis. Thus, strategies enabling activated platelet molecular imaging are of great interest; herein, a chemical protocol was investigated for coating superparamagnetic iron oxide nanoparticles with low molecular weight fucoidan, a ligand of P-selectin expressed on the surface of activated platelets. The physico-chemical characterization of the obtained product demonstrated successful

fucoidan coating and its potential as a T2 MRI contrast agent. The specificity and the strength of the interaction between fucoidan-coated iron oxide nanoparticles and human activated platelets was demonstrated by flow cytometry. Micromagnetophoresis experiments revealed that platelets experience magnetically induced motion in the presence of a magnetic field gradient created by a micromagnet. Altogether, these results indicate that superparamagnetic iron oxide nanoparticles coated with low molecular weight fucoidan may represent a promising molecular imaging tool for activated platelets in investigating human diseases. The results of the research into the influence of external magnetic fields are presented within a large number of sources, such as those that discuss the modeling of matter based on quantum theory [7]. The referenced article investigates the thermal entanglement in the two-qubit Heisenberg XY model with a nonuniform magnetic field, and the authors find that the entanglement and the critical temperature TC may be enhanced under a nonuniform magnetic field. Paper [8] then attempts to clarify the mechanism of the influence of an external magnetic field on radical-pair (RP) recombination from the perspective of a chemical model for the description of the sample properties. Magnetic field effects on the rate of RP recombination are the most widely understood mechanism by which magnetic fields interact with biological systems. However, the health related relevance of this mechanism of magnetic field sensitivity is uncertain because the best-known effects only become 3 significant at moderate magnetic flux densities above 1 - 10 mT. The authors of the study also summarize the theory of magnetic field effects on radical pair recombination and discuss the results obtained by investigating the photosynthetic reaction center and enzymes with RP intermediates. Similarly to our previous experiments [9], we tested the proposed numerical model and measured the material heating speed; further, a method was designed for accurate verification of heating speed changes depending on the external magnetic field. This paper also proposes a very detailed analysis of the influence of a magnetic field upon inanimate objects. Within the presented experiment, we measured the temperature change of a copper sensor in a stationary homogeneous and gradient magnetic field. Up to 10 times, the given sample was cooled down to the nitrogen boiling point (-195.80°C to 77.35 K); the sample was then removed at the pre-selected time and subsequently heated in another area to the temperature of -20 °C. Using the measuring apparatus and 3 temperature sensors (1 sensor measuring the temperature of the sample and 2 others to measure the ambient temperature), we recorded the temperature change in the sample and the required heating time. This experiment was repeated with four magnetic fields.

II. MATERIALS AND METHODS

2.1 The Electromagnetic field and particles

For a model with distributed parameters of the electromagnetic field, it is possible to use partial differential equations based on electromagnetic field theory to formulate a coupled model with concentrated parameters (in our case, particles) [9]. The details of the model are analyzed in this paper. The forces acting on a moving electric charge in the electromagnetic field can be expressed by means of the formula

$$f_e = \rho(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \text{in } \Omega, \tag{1}$$

where $\boldsymbol{B}$ is the magnetic flux density vector in the space of a moving electrically charged particle with the volume density ρ, v is the mean velocity of the particle, $\boldsymbol{v} = \mathrm{d}s/\mathrm{d}t$, s is the position vector from the beginning of the coordinate system o, t is the time, $\boldsymbol{E}$ is the electric intensity vector, and Ω is the definition region of the independent variables and functions. The properties of the area Ω are described by the mutual relationship between the intensities and inductions as defined by

$$rot\ \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} + rot(\boldsymbol{v} \times \boldsymbol{B}), rot\ \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} + rot(\boldsymbol{v} \times \boldsymbol{D}) \tag{2}$$

$$div\ \boldsymbol{B} = 0, div\ \boldsymbol{D} = \rho, \Omega, \tag{3}$$

where $\boldsymbol{H}$ is the magnetic field intensity vector, $\boldsymbol{J}$ is the current density vector, and $\boldsymbol{D}$ is the electric flux density vector. The material relations for the macroscopic part of the model are represented by the formulas

$$\boldsymbol{B} = \mu_0 \mu_r \boldsymbol{H}, \boldsymbol{D} = \varepsilon_0 \varepsilon_r \boldsymbol{E}, \tag{4}$$

where μ represents the quantity indexes of the permeabilities and permittivities, r denotes the quantity of the relative value, and 0 is the value of the quantity for vacuum. The relationship between the macroscopic and the microscopic (dynamics of particles in the electromagnetic field) parts of the model is described by the relations of force action on the individual

electrically charged particles in the electromagnetic field, and the effect is respected of the movement of electrically charged particles on the surrounding electromagnetic field according to [10]:

$$rot\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} + \boldsymbol{rot}(\boldsymbol{v}\times\boldsymbol{B}) - \frac{1}{\gamma} rot\left(\rho\boldsymbol{v} + jc\rho\boldsymbol{u}_t + \boldsymbol{J} + \frac{\gamma}{q_{e0}}\left(\frac{m_e d\boldsymbol{v}}{dt} + l\boldsymbol{v} + k\int_t \boldsymbol{v}\,dt\right)\right)$$

$$rot\,\boldsymbol{H} = \gamma\boldsymbol{E} + \rho\boldsymbol{v} + \gamma(\boldsymbol{v}\times\boldsymbol{B}) + \frac{\gamma}{q_e}\left(\frac{m_e d\boldsymbol{v}}{dt} + l\boldsymbol{v} + k\int_t \boldsymbol{v}\,dt\right) + jc\rho\boldsymbol{u}_t + \frac{\partial\boldsymbol{D}}{\partial t} + rot(\boldsymbol{v}\times\boldsymbol{D}). \tag{5}$$

The coupling of both models is formulated using both equation (5) and the formula

$$q_e(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}) + \frac{q_e}{\gamma}\left(\rho\boldsymbol{v} + jc\rho\boldsymbol{u}_t\frac{\partial(\boldsymbol{\varepsilon E})}{\partial t}\right) = \frac{m_e d\boldsymbol{v}}{dt} + \boldsymbol{v} + k\int_t \boldsymbol{v}\,dt. \tag{6}$$

The effect of the behaviour of the macroscopic model describing matter via the (old) quantum mechanical model of elements of the system can be observed using the fluxes of the quantities. The known quantities are magnetic flux ϕ, current flux I, and electric flux having the magnitude q:

$$\phi = \iint_\Gamma \boldsymbol{B}\cdot d\,\boldsymbol{S}\,,\ I = \iint_\Gamma \boldsymbol{J}\cdot d\,\boldsymbol{S}\,,\ q = \iint_\Gamma \boldsymbol{D}\cdot d\,\boldsymbol{S}\,, \tag{7}$$

where S is the vector of the oriented boundary (in a 3D model of the plane), and Γ is the boundary of the area Ω, in which the flux is evaluated. If there is a moving element of the system in the model with a scale difference expressed in orders, it is easier to describe the state and effect of the superposed electromagnetic field by expressing the time flux density τ. The time flux can be different or inhomogeneous in parts of the area Ω; it is then possible to write

$$t = \iint_\Gamma \tau\cdot d\,\boldsymbol{S}\,. \tag{8}$$

After expanding the expression with the time flux density for the Cartesian coordinate system o, x, y, z, we have

$$\boldsymbol{\tau} = \frac{1}{v_x(t)dx}\boldsymbol{u}_x + \frac{1}{v_y(t)dy}\boldsymbol{u}_y + \frac{1}{v_z(t)dz}\boldsymbol{u}_z \tag{9}$$

,

Where $\boldsymbol{u}_x$, $\boldsymbol{u}_y$, $\boldsymbol{u}_z$ are the base vectors of the coordinate system. The time density depends on the instantaneous velocity of the electrically charged particle motion $\boldsymbol{v}$ in the quantum mechanical model and on the element of length $d\ell$. Then, for the motion of the electrically charged particle along the element of the closed curve $d\ell$ (according to the microscopic interpretation), it is possible to write

$$\frac{\boldsymbol{E}}{q_e}d\ell = \left(\boldsymbol{\tau}^{-1}\times\boldsymbol{B}\right) \text{ in } \Omega. \tag{10}$$

Generally, if an electrically charged particle moves in a magnetic field having a magnetic flux density $\boldsymbol{B}$, and if the dimensions of the area Ω are many times larger than the electrically charged particle or groups of particles, it is necessary to consider the question of how the motion of the particle is influenced and what the observable oscillation changes are, namely the time flux density changes in parts of the area Ω. In the quantum-mechanical model of matter, the particles move in a nuclear structure, and their motion dynamics are changed by an external magnetic (static/quasi-stationary) field. Thus, a simple material heating test can be carried out to demonstrate the influence of an external magnetic field on the elementary model of matter. We tested three basic variants of the state of the macroscopically interpreted distribution of the external magnetic field having a magnetic flux density B [10]. Using the results obtained from the first experiments [2], we designed an exact technique for measuring the temperature change in the examined copper sample, Fig.1.

The conditions for the setting of the external magnetic field were taken over from the first experiment, and they were extended with a fourth setup:

1. The external magnetic field exhibits **low values-A** of magnetic flux density ***B***, and its distribution is homogeneous on the microscopic scale. We then have B = min (Earth's magnetic field), $\partial B_x/\partial x = 0$, $\partial B_y/\partial y = 0$, and $\partial B_z/\partial z = 0$ in at least one direction of the coordinate system and respecting the curl character of the field.

2. The external magnetic field exhibits **higher values-B** of magnetic flux density ***B***, and its distribution is homogeneous on the microscopic scale. We then have B = max, $\partial B_x/\partial x = 0$, $\partial B_y/\partial y = 0$, and $\partial B_z/\partial z = 0$ in at least one direction of the coordinate system and respecting the curl character of the field.

3. The external magnetic field is **inhomogeneous-C** on the macroscopic scale. We then have $\partial B_x/\partial x \neq 0$, $\partial B_y/\partial y \neq 0$, and $\partial B_z/\partial z \neq 0$, respecting the curl character of the field.

4. The external magnetic field exhibits **higher values and gradient-D** on the macroscopic scale. We then have B = max, $\partial B_x/\partial x \neq 0$, $\partial B_y/\partial y \neq 0$, and $\partial B_z/\partial z \neq 0$, respecting the curl character of the field.

2.2 Numerical model analysis

In accordance with [10], we used a simple analysis of the applied FeNdB permanent magnet blocks having the dimensions of 10x25x50 mm, surface magnetic flux density of Br = 1.1 - 1.2 T, and intensity of Hco = 750 – 1350 kA/m. During the experiment, an element evaluating the observed macroscopic behaviour of matter was inserted in the inhomogeneous magnetic field areas.

2.3 Experiments

The verification of the difference in the properties of the microscopic model of matter under the pre-defined condition of the external magnetic field was performed using a copper element (cube) having the dimensions of 10x10x10 mm, Fig. 1. A stainless steel wire of 1 mm in diameter attached to the cube facilitated all types of mechanical manipulation with the object. The temperature of the examined Cu cube was measured with a PT100 sensor (Heraeus MR828) of 3 mm in diameter placed inside the element. First, the cube was cooled down to -193°C; subsequently, after the temperature had stabilized,we heated the object to the ambient temperature of 20°C. The heating period was measured repeatedly, starting from -185°C and gradually proceeding to +10°C. These limits had been chosen with respect to suppressing the systematic measurement error in the experiment; the actual experiment is shown in Fig. 2. The Cu cube was heated through a copper block having the dimensions of 200x200x20 mm; this block exhibited a sufficient thermal capacity, and its temperature increased by less than 1°C during the experiments.

FIG. 1. THE MEASURED CU CUBE (MM) WITH THE PT100 SENSOR.

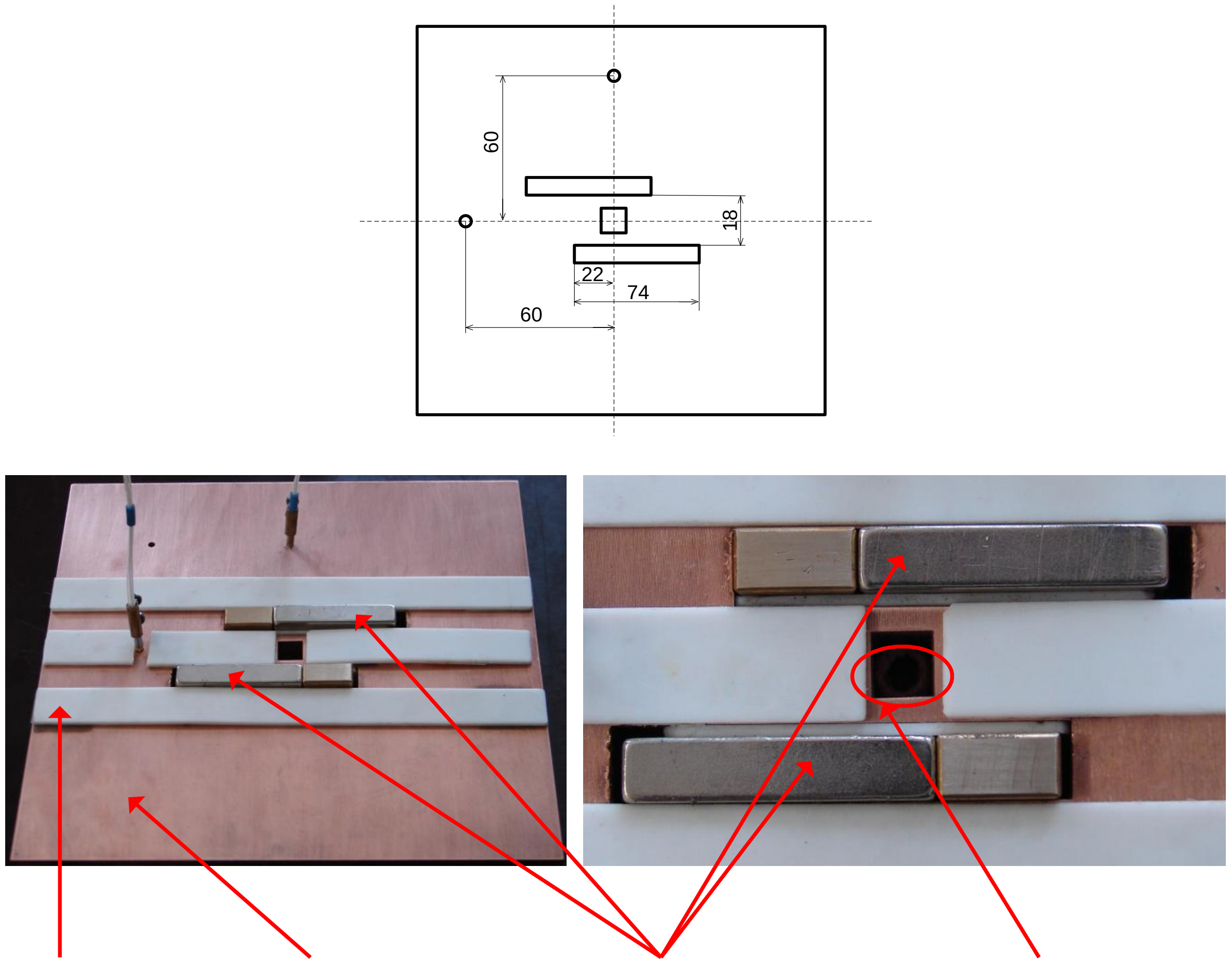

FIG. 2. DETAILED CONFIGURATION OF THE EXPERIMENT

Bores of 10x10 mm and 74x12 mm were made in the Cu plate to allow insertion of the cube and the permanent magnets, respectively, with the distance of 18 mm between the bores (Fig. 2). In our experiments, we used FeNdB permanent magnet blocks having the dimensions of 10x25x50 mm and exhibiting the surface magnetic flux density of Br = 1.2 T and intensity of Hco = 850 kA/m. The seating of the permanent magnets in the Cu block grooves (Fig. 2) facilitated the formation of three types of magnetic field with a flux density B and angle ϕ (the angle ϕ is found between B and the axis dividing the magnets). The magnetic fields were as follows: a) a homogeneous field of the first type, exhibiting the intensity of 270 mT and ϕ = 90o; b) a homogeneous field of the second type, exhibiting the intensity of 250 mT and ϕ = 64o; and c) a gradient field having the maximum gradient of 19 mT/m and ϕ = 69o. The detailed configuration of the fields is shown in Fig. 3a, and the results of the numerical analyses are presented in Fig. 3b. The magnets were separated from the Cu block with a teflon band of 1 mm in thickness to reduce the heat flow into the cube (the configuration is indicated in Fig. 2). The Cu block heating was monitored by two PT100 sensors; while the first one was placed at 60 mm from the cube on the axis passing between the magnets, the second one was located at 60 mm on the axis perpendicular to the magnets and passing through the centre of the cube. The cube and block temperatures were sensed by the three temperature probes and recorded via data acquisition/switch unit HP54070A. The aim of the experiment was to repeat the previous measurement [10] and to verify its results.

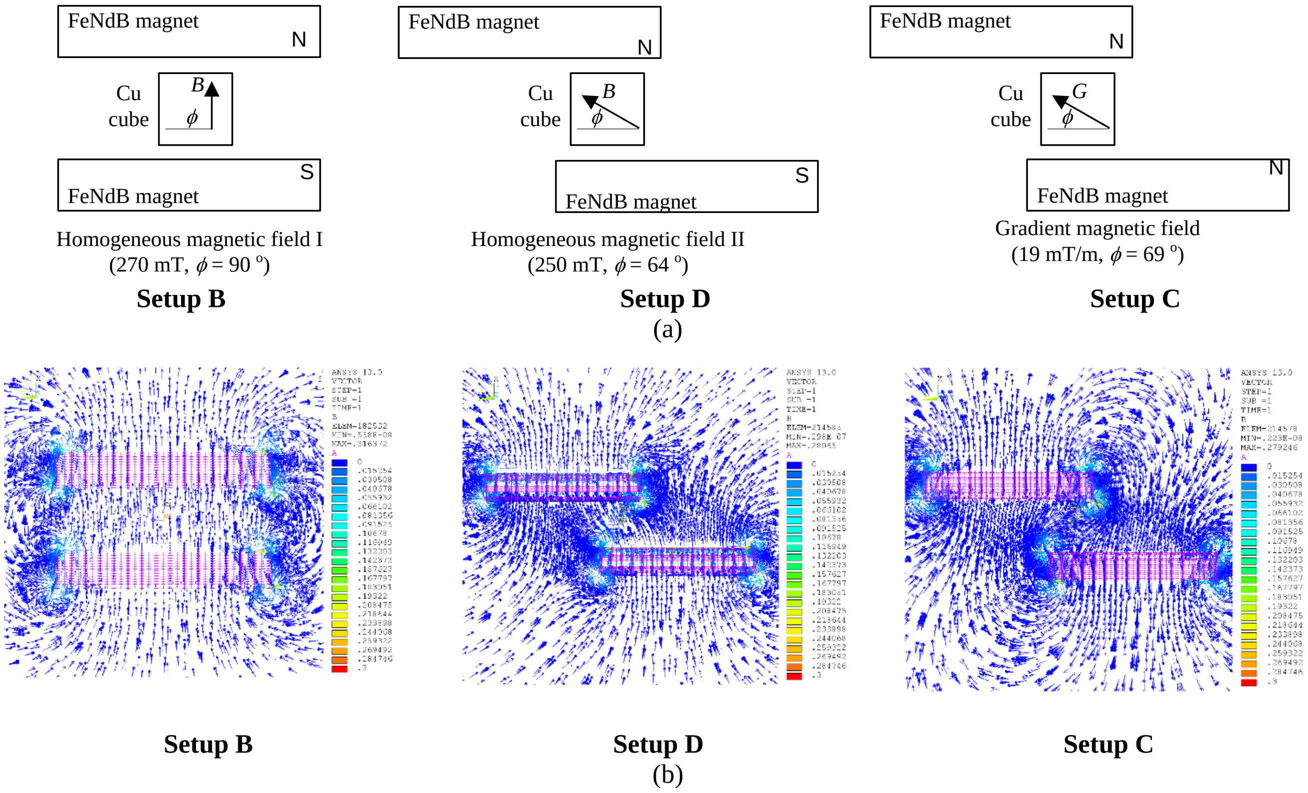

FIG. 3. (A) DETAILED CONFIGURATION OF THE MAGNETIC FIELDS; (B) DETAILED RESULTS OF THE NUMERICAL ANALYSES: MAGNETIC FLUX DENSITY

During the measurement, the Cu block was positioned on a wooden plate, either with or without the magnets. In the measurement cycle excluding the influence of an external magnetic field, brass blocks were inserted instead of the magnets; the blocks exhibited a thermal flow approximately identical to that of the magnets. The Cu cube was immersed in liquid nitrogen and cooled until its temperature stabilized; subsequently, the cube was mechanically transferred to the Cu block, and the temperatures were measured continuously during the process. The heat flow from the block warmed the cube, increasing its temperature until the temperatures levelled off. At this point, the measurement was completed. An example of temperature waveforms during on measurement cycle is presented in Fig. 4.

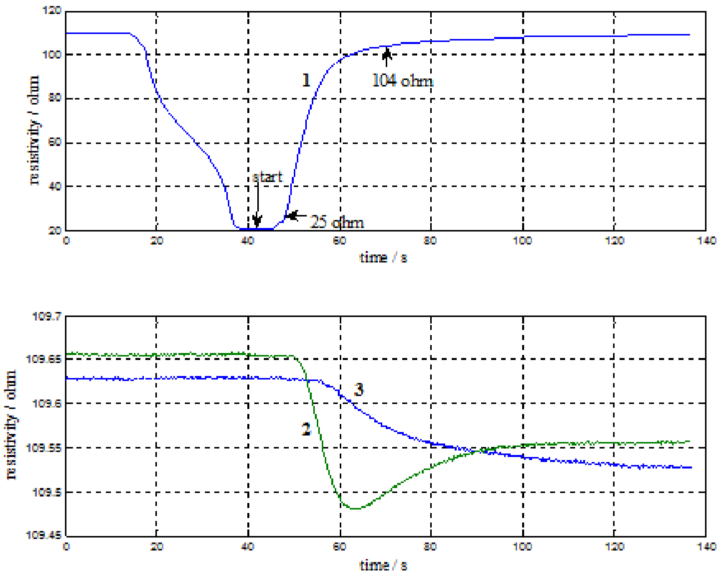

FIG. 4. EXAMPLES OF TEMPERATURE WAVEFORMS DURING ONE MEASUREMENT CYCLE: 1 – CU CUBE; 2 – TEMPERATURE OF THE CU BLOCK BETWEEN THE MAGNETS AT THE DISTANCE OF 60 MM FROM THE CENTRES OF THE MAGNETS; 3 – TEMPERATURE OF THE CU BLOCK AT A POINT LOCATED 60 MM (AND IN A PERPENDICULAR DIRECTION) FROM THE CENTRAL SECTION BETWEEN THE MAGNETS.

The four-terminal impedance measurement (PT100) is repeated ten times for the configurations without a magnetic field, with the homogeneous magnetic fields of the first (setup B) and the second (setup D) types, and with the gradient field (setup C), Fig. 3. To evaluate the heating speed in the Cu cube, we selected two impedance levels for the Pt sensor, namely 25 Ω (-185 ^{o}C) and 104 Ω (+10 ^{o}C), and set the heating times between these levels. The exact times were recorded together with the temperatures measured by the three sensors. The quantization step value was 193 ms. To increase the measurement accuracy, the measured values were interpolated in the immediate vicinity of the selected levels; we also evaluated the heating times to achieve the given purpose.

III. RESULTS

It follows from the experiments that the homogeneous magnetic field of the second type (setup D) with the magnetic flux density of B = 250 mT exhibits the lowest time flux density τ. In the gradient magnetic field (setup C) exhibiting the magnetic flux gradient of dB / dx ≈ 19 T/m, the time flux density τ is higher compared to the setup D. The homogeneous magnetic field of the first type (setup B; B = 270 mT) perpendicular to the heat flow direction provides a higher time flux density τ compared to the magnitude observed in the Earth's magnetic field, B = 50 µT (setup A). Tab. 1 comprises the values measured during the experiment. The four-terminal impedance sensing (PT100) is repeated 10 times for the configurations without a magnetic field (setup A), with the magnetic fields of the first (setup B) and the second (setup D) types, and with the gradient field (setup C).

TABLE 1
MEASURED HEATING SPEED VALUES IN THE EXAMINED SAMPLE.

Measurement	Time Difference / s			
	No Field	Homogeneous Field I	Gradient Field	Homogeneous Field II
1	36,64928955	37,71446887	34,48015863	22,82040233
2	38,06576586	41,62355197	36,4855295	28,36592113
3	39,7085593	38,67162785	39,54154481	29,79942564
4	41,18051012	40,20475581	37,88963473	31,49956476
5	42,77172513	38,4903284	38,57823307	33,26028898
6	41,03824944	38,19525093	38,49898872	33,13491397
7	44,16877291	38,91989879	39,23681201	34,11134567
8	45, 44665016	37,31208691	38,8054958	33,56003627
9	42,74964147	39,09137363	38,70252762	34,34513303
10	45,26375993	41,99884713	44,30902191	34,38462373
Mean Value	41,70429239	39,22221903	38,65279468	31,21078131
Standard Deviation	2,801316176	1,495505043	2,36366684	3,482702384
Decrease [%]	0	-5,6	-7,317	-24,4
Setup	A	B	C	D

The experiment was repeated multiple times under identical conditions, providing identical results. The results obtained within the previous measurement [2], in which the process of heating and cooling the Cu sample differed to a certain extent, were comparable. In the actual experiment, the heat flow warming the Cu cube should arrive only from the Cu block, not from the top and bottom sides of the cube; for this purpose, these sides of the cube are to be surrounded by air to reduce heat flow from undesired directions.

The first paragraph under each heading or subheading should be flush left, and subsequent paragraphs should have a five-space indentation. A colon is inserted before an equation is presented, but there is no punctuation following the equation. All equations are numbered and referred to in the text solely by a number enclosed in a round bracket (i.e., (3) reads as "equation 3"). Ensure that any miscellaneous numbering system you use in your paper cannot be confused with a reference [4] or an equation (3) designation.

IV. CONCLUSION

Repeated measurement has shown that the heating time is shorter than in the previous experiments [10]; this condition was achieved via changing the entire measurement task. However, the relative ratio of the heating time is comparable to the previous cycles [10], mainly due to the various magnetic field configurations (setup **A** to **D**). Significantly, the homogenous field the second type (setup **D**) exhibits the most distinctive reduction of the cube heating time: the total time is only 31.2 ms. All measurements for the different settings of the external magnetic field are outside the range of measurement inaccuracy

tolerance; thus, it can be proved that the external magnetic field changes the dynamics of the model of matter, and if time density is applied as a quantity, it can be stated that this density changes its value in individual cases.

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